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An evaluation of wind energy potential at Kati Bandar, Pakistan

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ABSTRACT

As a developing nation of energy-starved people, Pakistan urgently needs new sources of affordable, clean energy. Wind energy is potentially attractive because of its low environmental impact and sustainability. This work aims to investigate the wind power production potential of sites in south-eastern Pakistan. Wind speed data measured over a one-year period at a typical site on the south-east coast of Pakistan are presented. Frequency distributions of wind speed and wind power densities at three heights, seasonal variations of speed, and estimates of power likely to be produced by commercial turbines are included. The site investigated is found to be a class 4 wind power site with annual average wind speed of 7.16 m/s and power density of 414 W/m^2 at 50 m height. The site is, therefore, likely to be suitable for wind farms as well as small, stand-alone systems.

Contents

1. Introduction

The energy supply per capita is a common indicator of the state of development of a country. Pakistan, a developing country of 170 million people, has an energy supply per capita of 0.38 tons of oil equivalent (TOE) per year compared to the world average of 1.64 TOE [1]. Moreover, the energy supply has been more or less static for the last several years. Similarly, the yearly per capita electricity consumption in Pakistan is 424 kWh, compared to world average of 2603 kWh [2] and there is a large gap between demand and supply. About 68% of Pakistan's people live in rural areas comprising some 125,000 villages, 37% of which are still without electricity. The poorer sections of the society are especially hit by lack of access to electricity. The World Bank estimates that about 48% of poor households (as compared to 24% of other households) do not have access to electricity in Pakistan. Provision of even a minimal quantity of electricity to these people can bring a huge improvement in their quality of life.

Pakistan has a currently installed capacity of 19,566 MW of electricity generation, of which about 33% is hydroelectricity, 64% is from fossil fuels and the rest from nuclear energy [1]. Hydroelectricity is much cheaper as well as less polluting; however, its share in the total generation has been decreasing steadily, from 70% of total in the 1960s to the current 33%. Not only has this trend caused a huge increase in electricity prices, but it has also produced higher air pollution. It is estimated that carbon dioxide emissions by the power producing sector have increased almost 15-fold over a twenty-year period.

The large gap between demand and supply of electricity, increasing cost of imported fossil fuels and worsening air pollution demand an urgent search for energy sources that are cost-effective, reliable and environment-friendly. There has been a lot of recent interest worldwide in developing renewable energy sources. The technology for exploiting wind energy, in particular, has matured

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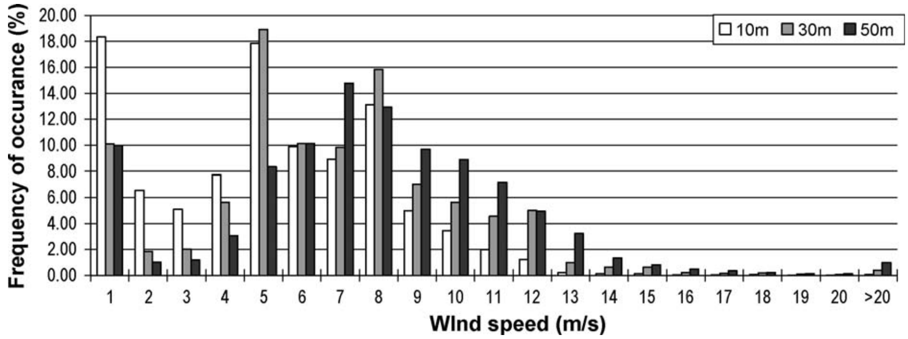

Fig. 1. Frequency distribution of wind speed at Kati Bandar over the year.

to the point that electricity produced from wind turbines now competes in cost with that produced from conventional sources, especially when the cost of environmental damage is factored in. Due to its wide availability and low environmental impact, wind energy is the fastest growing energy resource today. The world-wide capacity of wind power generation reached 121,188 MW at the end of 2008, with a growth rate of 29% per year [3]. Pakistan, however, is yet to appear on the world wind energy map.

Wind energy is thus a potentially attractive source of renewable energy whose availability needs to be investigated. To that end, Pakistan Meteorological Department has collected wind data in coastal areas of Pakistan, some 1100 km over latitude 24–27°N, longitude 62–69°E approximately, including sites up to 100 km inland from the coast. Forty-one wind measuring stations were set up at the various sites considered to be potentially windy areas that also possess other desirable qualities of a wind power production site. Triangular hollow type towers were erected at each location as far away as possible from local obstructions, taking care to select a site that is representative of the location in general. Two digital wind speed calibrated sensors (model# 40c NRG Systems) were installed at 10 m and 30 m height. One temperature sensor (model# 110s NRG Systems) and one wind direction sensor (model# 200p NRG Systems) were also installed at 10 m and 30 m height. Zero error values (uniquely determined for each sensor) were provided by the manufacturer. The data logger sampled values every half a second, and recorded one-minute average and ten-minute extremes of wind speed, one-minute average of wind direction and five-minute average of temperature. This paper presents the data collected at Kati Bandar, a small village east of Karachi on the coast of Sindh.

Assessments of wind energy potential have been undertaken in several countries in the region as reported in recent literature [4–6]. Reviews of renewable energy technology prospects in Pakistan [7] and the development of wind energy in Pakistan in particular [8] have been published, but this is the first report assessing wind energy potential in Pakistan using measured wind speed data.

In the next sections, the wind speed data are analysed, the available power in wind is calculated and estimates of electrical power potentially generated by some commercial turbines are presented. This is followed by a discussion of the results and conclusions.

2. Kati Bandar wind potential evaluation

Wind speed data are summarized in a number of ways in the literature, including averages and variances, frequency histograms, and theoretical frequency distributions fitted to the data. Rayleigh and Weibull distributions are considered to be the most suitable for representing wind speed variations. In addition to yearly statistics, monthly and diurnal variations in wind speed are also of interest. The wind power potential of a site depends both on wind speeds and the proportion of time for which these speeds are available. In addition, the air density, the height of the turbine tower, and the design of turbine affect the power produced. All of these aspects are considered in the following sections.

2.1. Wind speed characterization

The variation of wind speed with height is given by the log law:

$$\frac{U(z)}{U_r} = \frac{\ln(z/z_0)}{\ln(z_r/z_0)} \tag{1}$$

where $U(z)$ is the wind speed at height z, U_r is the reference wind speed at reference height z_r, and z_0 is the surface roughness length, which characterizes the roughness of the terrain. Values of surface roughness length for various types of terrain are given in the literature, e.g., [9]. In this research, z_0 was calculated from Eq. (1) using the measured speeds at 10 m and 30 m height. Eq. (1) was

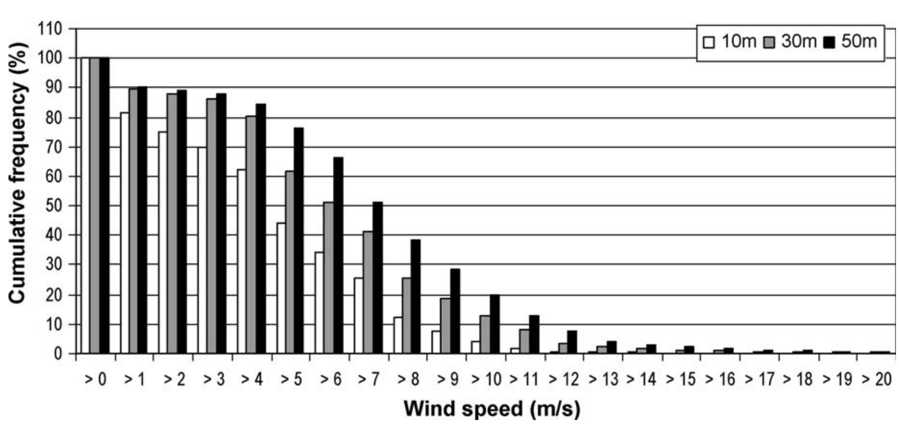

Fig. 2. Cumulative frequency distribution of wind speed at Kati Bandar over the year.

then used to estimate wind speeds at 50 m height, since commercial wind turbines commonly have a hub height of 50 m or more.

A histogram of the percentage frequency of wind speed for the year is shown in Fig. 1 and the cumulative frequency distribution, which shows the percentage of time the wind speed exceeds a certain value is drawn in Fig. 2. It can be noted that, for example, the wind speed at 50 m height is greater than 4 m/s for 85% of the time in the year. The 4 m/s limit is important since this is the cut-in speed of many commercial turbines. The cut-out speed is generally 20–25 m/s and such speeds are rare at this site.

The Weibull probability density function, which is most commonly used to characterize wind speed distribution, is given by

$$p(U) = \left(\frac{k}{c}\right)\left(\frac{U}{c}\right)^{k-1}\exp\left[-\left(\frac{U}{c}\right)^{k}\right] \tag{2}$$

where c is a scale factor (in units of speed) and k is a shape factor. Higher values of k indicate sharper peaked curves while lower k means more flat or more evenly distributed speeds. A value of 2 for k reduces the Weibull distribution to the Rayleigh distribution, another commonly used function for wind speeds. To fit the

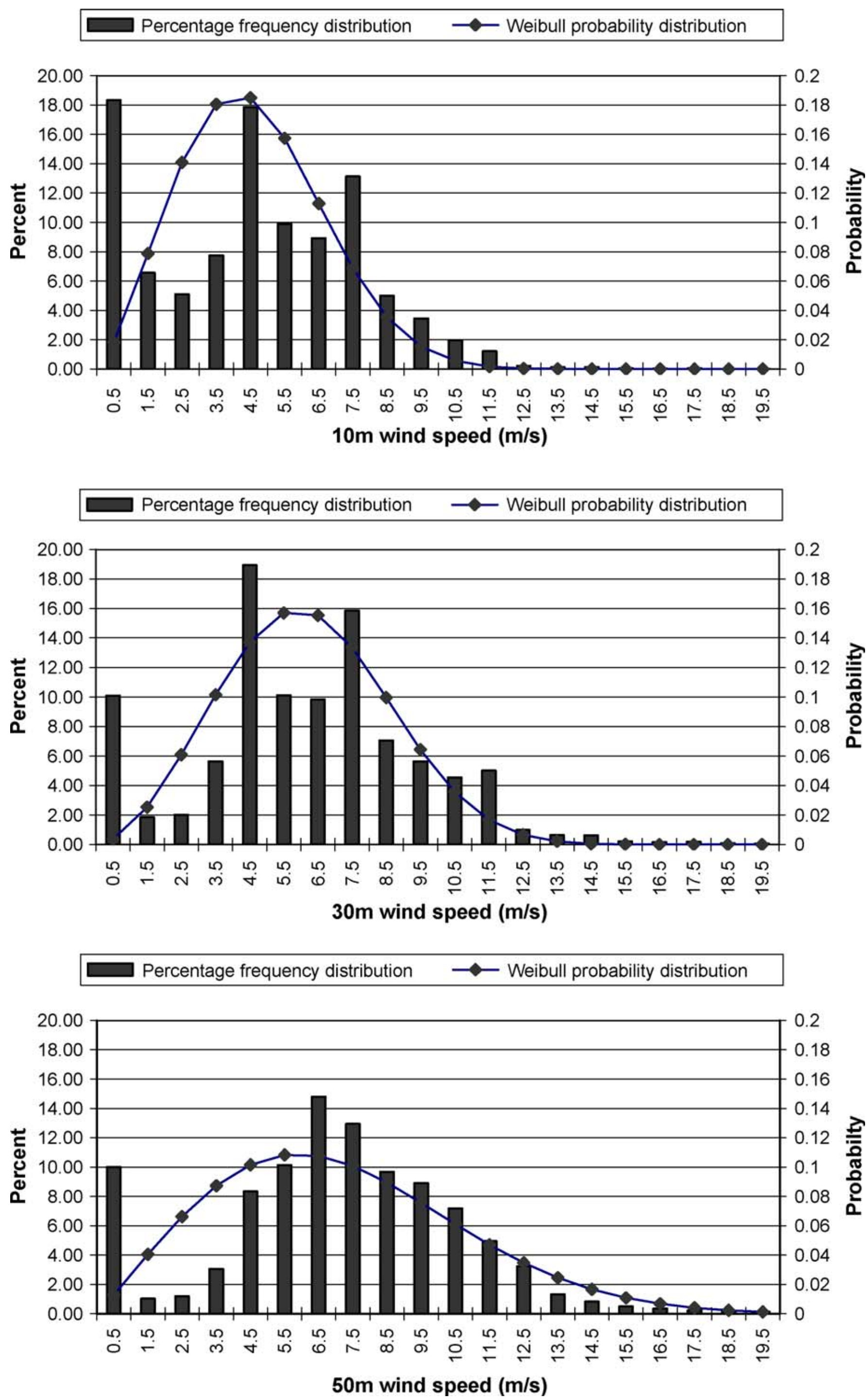

Fig. 3. Weibull distributions of wind speeds for different heights at Kati Bandar over the year.

Weibull distribution to measured data, a number of methods are reported in the literature of which the maximum likelihood method is considered optimal [10]. To estimate Weibull parameters from speed data using the maximum likelihood method the following equations are used:

$$k = \left(\frac{\sum_{j=1}^{N} U_j^k \ln(U_j)}{\sum_{j=1}^{N} U_j^k} - \frac{\sum_{j=1}^{N} \ln(U_j)}{N} \right)^{-1} \quad (3)$$

$$c = \left(\frac{1}{N} \sum_{j=1}^{N} U_j^k \right)^{1/k} \quad (4)$$

where U_j is the speed in timestep j and N is the total number of nonzero wind speed data points. Eq. (3) must be solved iteratively for k (with $k = 2$ a reasonable starting point), and then Eq. (4) can be solved for c.

Fig. 3 shows the Weibull distributions of wind speeds at different heights superposed on the frequency distributions. Note that frequency is shown as percent while Weibull distribution gives the probability of occurrence of wind speeds. Weibull distributions typically fit badly at low speeds but this is acceptable since very little power is produced at low speeds. The Weibull distribution is seen to be a reasonably good fit for the wind speeds data collected at Kati Bandar.

The annual average and standard deviation of wind speed, the Weibull parameters, and the average available wind power density (defined below) at different heights are given in Table 1. Separate characterization for each month was also carried out as shown in Table 2. The monthly average wind speeds and power densities are shown plotted in Figs. 4 and 5, respectively. The figures show a large seasonal variation, with wind average speeds at 50 m height varying from a low of 4.4 m/s in November to a high of 11.3 m/s in July. Wind speeds are higher in the summer season (April–September) but generally suitable for good power production all year, except possibly in the period November–January.

2.2. Wind power characterization

The average wind power density is the average power available per unit area of the turbine rotor, and can be calculated as:

$$\frac{\bar{P}}{A} = \frac{1}{2} \rho \frac{1}{N} \sum_{j=1}^{N} U_j^3 \quad (5)$$

For Kati Bandar, the average power density available over the whole year is found to be 414 W/m^2 at 50 m height, which translates into total available yearly energy density of 3627 kWh/m^2 of rotor area.

The actual power a particular turbine is expected to produce at this site depends on turbine rotor area, hub height, and the efficiency (or capacity factor) of the turbine. Given the power curve of a turbine (i.e., the experimentally determined relation between wind speed and turbine power output, $P_W(U)$) and the wind speeds, it is possible to calculate the average power of the wind turbine as:

$$\bar{P}_W = \frac{1}{N} \sum_{j=1}^{N} P_W(U_j) \quad (6)$$

Table 1
Wind speed parameters at Kati Bandar for the year.

	U_{avg} (m/s)	St Dev	c (m/s)	k	P/A (W/m^2)
10 m height	4.71	2.20	5.18	2.38	151
30 m height	6.26	2.50	6.95	2.79	289
50 m height	7.16	3.65	8.09	2.08	414

Table 2
Wind speed characterization at Kati Bandar by month.

	U_{avg} (m/s)	St Dev	c (m/s)	k	P/A (W/m^2)
10 m height					
January	2.88	2.23	3.13	1.32	49
February	3.26	2.92	3.40	1.13	97
March	3.48	2.31	3.87	1.56	66
April	5.30	2.27	5.97	2.51	143
May	7.59	2.60	8.48	3.20	364
June	6.45	2.33	7.22	3.02	229
July	8.62	2.05	9.41	4.77	458
August	5.76	1.74	6.39	3.67	150
September	5.66	1.73	6.28	3.62	142
October	2.70	1.86	2.99	1.50	33
November	2.07	1.99	2.11	1.05	29
December	2.80	2.38	2.97	1.19	54
30 m height					
January	4.02	2.74	4.45	1.51	107
February	4.90	3.43	5.41	1.47	201
March	5.05	2.41	5.70	2.23	136
April	7.31	2.29	8.13	3.53	311
May	9.52	2.86	10.55	3.69	671
June	8.09	2.73	9.02	3.26	436
July	10.41	2.86	11.47	4.07	847
August	6.93	1.94	7.64	3.98	252
September	7.05	1.93	7.76	4.08	263
October	4.27	1.90	4.82	2.41	77
November	3.56	2.23	3.98	1.66	65
December	4.03	2.70	4.48	1.54	104
50 m height					
January	4.80	3.29	5.32	1.51	183
February	5.77	3.71	6.44	1.62	288
March	5.96	2.71	6.72	2.35	214
April	8.46	2.45	9.35	3.84	465
May	10.58	3.04	11.69	3.88	905
June	9.03	2.95	10.05	3.37	597
July	11.30	3.12	12.46	4.06	1086
August	7.68	2.15	8.47	3.99	342
September	7.91	2.14	8.71	4.14	370
October	5.21	2.29	5.87	2.44	139
November	4.41	2.77	4.93	1.66	125
December	4.82	3.19	5.36	1.56	176

and the total energy output is obtained by multiplying with the number of time intervals (i.e., hours).

Using binned wind speed data, the power generated can be calculated from

$$\bar{P}_W = \frac{1}{N} \sum_{j=1}^{N_B} P_W(m_j) n_j \quad (7)$$

where n_j is the number of occurrences in the jth bin, the midpoint of which is m_j. N_B is the total number of bins.

As an example, the power generation potential of three commercial turbines of different sizes—Nordex N90/2300, Nordex S77/1500, and Nordex N27/150—has been calculated. Table 3 shows the parameters of each turbine [11], including the rated power, the rotor diameter, the hub height, the rated wind speed, and the cut-in and cut-out speeds. Table 4 shows the average power produced, total energy output over the year, and capacity factor of each turbine for this site. The capacity factor is defined as the turbine energy output divided by the theoretical output with the turbine running constantly at its rated power.

3. Discussion

The USA wind energy atlas defines seven wind power classes to categorize the wind energy resource at a site, ranging from class 1 (least energy) to class 7 (most energy). The 7.16 m/s annual average wind speed and 414 W/m^2 average power density at 50 m height put Kati Bandar in class 4, suitable for most wind turbine

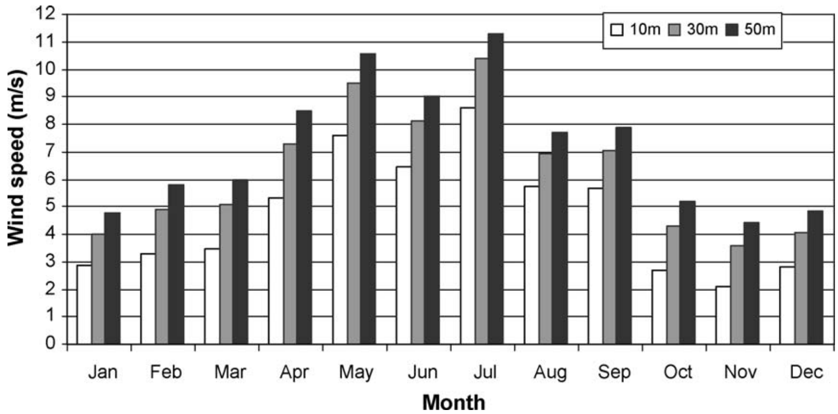

Fig. 4. Monthly average wind speeds at 10 m, 30 m and 50 m heights at Kati Bandar.

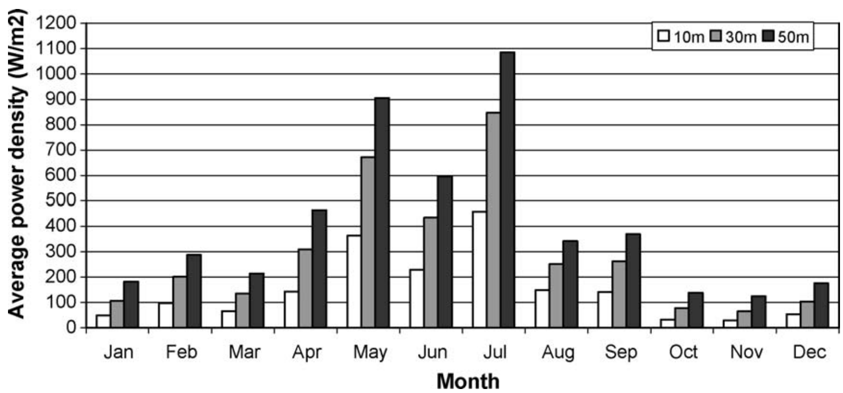

Fig. 5. Monthly average wind power density at 10 m, 30 m and 50 m heights at Kati Bandar.

applications, ranging from small, stand-alone turbines to large wind farms. While the large investment required for a wind farm needs a detailed analysis of the costs and benefits that is beyond the scope of this paper, a rough economic analysis of a stand-alone system to serve the local community is presented below.

Small, off-grid or mini-grid power systems based on renewable energy sources have many benefits. In many cases, it is simply not feasible to extend the main grid to a small, remote community. Even when electricity from the grid is available, it may be cheaper to use it only as a backup, e.g., for low-wind season. Winds at Kati Bandar are especially strong in summer months, when the cooling load creates a high electricity demand in the cities. It may be profitable to sell the extra electricity to the grid in that season.

Assuming that the 2900 people living in Kati Bandar use electricity at the national average rate of 424 kWh per year, the total energy requirement is 1230 MWh. Selecting the 150 kW N27/150 turbine, note first that it has a rotor diameter of 27 m and would thus likely be installed at a hub height of 30 m, instead of the 50 m height chosen for comparison purposes in Table 4. Using 30 m height wind speeds, the turbine output energy is calculated as 475 MWh per year. Let us assume that three such turbines are installed.

Turbine costs are estimated, using the thumb rule [12] of US $ 1000 per kWh, as $ 450,000. Installation costs are taken as a further 20% of turbine cost and operation and maintenance as 2% of turbine cost per year. With a turbine life of 20 years and a real interest rate of 5%, the cost of electricity is calculated as 3.7 cents per kWh—at present day prices. This order-of-magnitude analysis indicates that an off-grid wind power system for local communities is likely to be feasible and should be seriously considered.

It should be noted that although the total energy provided by the turbines over the year meets the needs easily, the power produced will vary considerably, both over a day and over the seasons. A backup or energy storage system (such as diesel generators and batteries, or grid connection) would thus be required for stand-alone (off-grid) systems, adding to the cost significantly. Furthermore, although the calculated price of electricity is reasonable on an international standard, the majority of the people in the rural community probably cannot afford it. It is, therefore, important to reduce the price as much as possible.

In general, current commercial turbines are designed for high-wind sites and do not perform as well in low winds. Turbines

Table 3
Parameters of selected Nordex wind turbines.

Turbine model	N90/2300	S77/1500	N27/150
Rated power (kW)	2300	1500	150
Rotor diameter (m)	90	77	27
Hub height (m)	80	61.5	30
Cut-in wind speed (m/s)	4	4	4
Rated wind speed (m/s)	13	15	14
Cut-out wind speed (m/s)	25	20	25

Table 4
Expected yearly power production[a] by selected Nordex turbines.

	Turbine		
	N90/2300	S77/1500	N27/150
Average power (kW)	831	560	71
Energy produced (MWh)	7218	4860	618
Capacity factor	0.36	0.37	0.47

[a] Based on assumed 50 m hub height.

designed to take advantage of local wind regimes will capture more energy, thus lowering the cost. Manufacturing the turbines locally could also bring down the costs substantially.

4. Conclusions

As a developing nation of energy-starved people, Pakistan urgently needs new sources of affordable, clean energy. Providing even a minimal amount of electricity to roughly half the poor households currently without access would bring a huge improvement in the quality of life. Wind energy is an attractive option because of its low impact on environment, sustainability, and reasonable costs. An evaluation of the wind resource available at Kati Bandar on the coast of Sindh shows that it is a class 4 wind power site, indicating its suitability for both large and small wind power projects. However, the price of electricity produced, though probably reasonable by international standards, may be unaffordable for poor, rural communities. To lower the costs, it would be necessary to adapt turbine designs to local conditions and to manufacture them locally.

References

[1] Ministry of Finance, Government of Pakistan. Economic Survey of Pakistan 2007–08. http://www.finance.gov.pk/finance_economic_survey.aspx.
[2] International Energy Agency. IEA Energy Statistics. www.iea.org.
[3] World Wind Energy Report 2008. www.wwindea.org.
[4] Rehman S. Wind energy resources assessment for Yanbo, Saudi Arabia. Energy Conversion and Management 2004;45:2019–32.
[5] Lu L, Yang H, Burnett J. Investigation on wind power potential on Hong Kong islands—an analysis of wind power and wind turbine characteristics. Renewable Energy 2002;27:1–12.
[6] Vogiatzis N, Kotti K, Spanomitsios S, Stoukides M. Analysis of wind potential and characteristics in North Aegean, Greece. Renewable Energy 2004;29:1193–208.
[7] Chaudhry MA, Raza R, Hayat SA. Renewable energy technologies in Pakistan: prospects and challenges. Renewable and Sustainable Energy Reviews 2009;13:1657–62.
[8] Mirza UK, Ahmad N, Majeed T, Harijan K. Wind energy development in Pakistan. Renewable and Sustainable Energy Reviews 2007;11(9):2179–90.
[9] Manwell JF, McGowan JG, Rogers AL. Wind energy explained. New York: John Wiley; 2002.
[10] Seguro JV, Lambert TW. Modern estimation of the parameters of the weibull wind speed distribution for wind energy analysis. Journal of Wind Engineering and Industrial Aerodynamics 2000;85:75–84.
[11] Nordex AG. Product Brochures. http://www.nordex-online.com.
[12] Danish Wind Energy Association. Wind Energy Guided Tour. www.windpower.org/en/tour.